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Irradiating the Environment:

Radiological Impacts in Life Cycle Assessment

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Abstract

One of the main shortcomings of Life Cycle Assessment (LCA) when applied to the Nuclear Fuel Cycle, is that there is currently no recognised procedure to deal with radionuclide emissions in the Impact Assessment stage. A framework which considers both human and environmental impacts is required and a methodology which is compatible with the other impact assessment approaches in LCA must be developed. It is important that the discussion is not only restricted to concepts, but that a working methodology is developed which can be readily applied by LCA practitioners. A provisional method is available for assessing radiological impacts on human health, but no consideration has been given to potential effects on the environment. A methodology is proposed in this paper which assesses irradiation of the environment using Environmental Increments (EI) as the quality standard. This approach is based on the same principles as for the Ecotoxicity classification group, and it represents a working methodology which can be continuously improved as knowledge in the area increases.

Keywords: Life Cycle Assessment; Impact Assessment; radiation, radionuclides; environmental increments; environmental irradiation

1 Introduction

General aspects of radiation in Impact Assessment have already been discussed by HEIJUNGS (1994), who suggested that a proposed radiation category should be subdivided into emissions of radioactive substances and emissions of radiation, and that a distinction should be made between external and internal impacts on human health. Emissions of radiation only contribute to external impacts caused by exposure, while emissions of radioactive substances may contribute to both external exposure and internal impacts through intake of food and water, or by breathing. The only provisional method currently available for assessing the potential effects of internal radiation is similar to that used for human toxicity and is based on Annual Limits on Intake (ALI) as the quality standard. This approach does not include any fate data, and it must be stressed that better characterisation of the human impacts of radiation is required. This is also emphasised by HEIJUNGS (1994) who outlines a possible way forward using multi-media models and a reference isotope in a similar manner to what has been proposed for the assessment of toxic releases (see GUINÉE, 1996). It is not the intention of this paper, however, to discuss possible improvements in the human radiation category, but to highlight the problem that the above ideas only concentrate on impacts on human health.

The possibility of radionuclides harming ecosystems is also of concern and the potential effect of accumulation of radionuclides in the environment should not be ignored. In the ICRP recommendations on radiological protection in 1977 it was stated that "if man is adequately protected, then other living things are also likely to be sufficiently protected" (ICRP, 1977). This statement is generally accepted by the NCRP (NCRP, 1991) and IAEA (IAEA, 1992), although it is recommended that exposure of other populations in the ecosystem should be assessed and included in any consideration of the overall acceptability of a proposed or expected waste disposal practice (NCRP, 1991). The fate of individual organisms is, generally, not the major concern but rather the response and maintenance of endemic populations. This view has been challenged by AMIRO et al. (1993b) as it assumes that humans are one of the most radiation-sensitive species because they are long-lived mammals. It implies that individual human life is valued more than individuals of other species and that if humans are selected as the critical indicator species, ecological protection is achieved. It is argued that this is based on limited evidence and that it is only valid when both humans and other biota inhabit the same part of the environment. Non human organisms could be exposed to higher concentrations because of habitat differences, and there could be an impact on certain species without a concomitant impact on humans (THOMPSON, 1988). This paper proposes a new impact category called Environmental Irradiation which will assess the environmental acceptability of releases of radionuclides from nuclear facilities. The approach selected is consistent with the other characterisation methods in LCA, and the methodology it most resembles, Ecotoxicity, is briefly described.

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The characterisation stage in LCA is based on a linear weighting factor which expresses the potential contribution to a category per mass or other quantity of an input or an output:

$$C_{ij} = M_j W_{ij} \tag{1}$$

where C_{ij} potential contribution to the impact i from the input or output j
M_j quantity or mass of input or output j
W_{ij} weighting factor

In the case of Ecotoxicity, this weighting factor (also commonly called classification factor or characterisation factor) is expressed as the product of an effect factor (E) and a fate factor (F):

$$W_{ij} = E_j \times F_j \tag{2}$$

where E_j Effect factor for substance j
F_j Fate and exposure factor for substance j, taking into account the route of exposure between the emission and the receptor experiecing the effect

The Effect factor is expressed in terms of a toxicological or ecotoxicological impact or of a quality standard for the substance in question, while the Fate factor describes the fate of the component from emission to its exposure to the target system.

During the classification of ecotoxic emissions, a distinction is made between aquatic (salt and freshwater) and terrestrial ecosystems, and separate contributions are calculated for emissions, to air, water and soil. Emissions to groundwater and sediment are included under aquatic and terrestrial Ecotoxicity respectively, as emissions to these media are mainly indirect and cannot be seen in isolation from pathway processes. There is very little data available about the ecotoxic effects of substances taken up through the atmosphere, and these emissions are only assessed for their human toxicological effect.

The quality standard used when assessing Ecotoxicity is the Maximum Tolerable Concentration (MTC). This is an approximation of the critical concentration at which 95 % of the individuals in the water or soil ecosystem are protected, based on standards for individual substances (HEIJUNGS et al., 1992). The effect factor is inversely proportional to the maximum acceptable concentration and is expressed by:

$$E_j = \frac{1}{MTC_j} \tag{3}$$

where MTC_j Maximum tolerable concentration determined for substance j in a given medium

The ecotoxicological exposure factor depends on the partition, degradation and immobilisation processes in the environment. Several methodologies have been proposed to deal with this, but for the time being the fate factor is often set to 1. The weighting factor for Ecotoxicity is therefore given by:

$$W_{ij} = \frac{1}{MTC_j} \tag{4}$$

2 Environmental Irradiation

A similar weighting factor can be developed for different radionuclides to assess their potential impacts on the environment. The resulting category will be called Environmental Irradiation, and this paper proposes to base it on Environmental Increments (EIs) as the quality standard. These values have been introduced by AMIRO (1993a) as a screening tool to identify potentially unacceptable concentrations arising from a nuclear waste disposal project. The work focuses on the underground disposal of long-lived radioactive wastes and the data used is relevant to Canadian plans for geological disposal of nuclear waste in the Canadian Precambrian Shield.

AMIRO introduces a set of Environmental Increment (EI) factors for the most important radionuclides in nuclear waste. These are increments in the baseline environmental concentration of different radionuclides which represent the concentration that can be added to soil and water without causing detectable effects. This is based on the assumption that the biota are already exposed to radionuclides in the environment and therefore can tolerate some exposure. The concentration of radionuclides in the abiotic part of the ecosystem varies in time and space, and this variability increases with increasing spatial and temporal scales. The scales and corresponding variability depend on the nature of the ecosystem (AMIRO, 1993b). AMIRO assumes that a definable ecosystem has a temporal scale of greater than one year and a spatial scale of more than one hectare, and that variations within these scales are tolerated by the ecosystem. Hence, additional radionuclides will not be ecologically significant if the concentrations remain within the local natural variability. It is arbitrarily assumed that an additional concentration of up to one standard deviation of the "background noise" is environmentally acceptable and equal to the EI (AMIRO, 1993a). In effect, EI values are used as a conservative proxy for No Effect Concentrations, in the absence of direct ecotoxicological data but using the observation that these variations have no observable ecotoxicological effect.

For the most common radionuclides, the EI values are found from spatial lognormal or normal distribution data of the elements in the environment. In the case of rare or virtually non-existent radionuclides, baseline data is not available and alternative techniques are used. In some cases it is assumed that variability equals a constant fraction of the mean concentration and this is equated to the EI; in other cases the EIs are based on data from other radionuclides with analogous chemical behaviour. A more detailed account may be found in AMIRO (1993a).

This framework may be applicable as a basis for quantifying the environmental impact of radionuclides in the impact assessment stage in LCA. The EI values derived by AMIRO (1993a) can be used as indicators of whether an area might become "polluted" and can be treated as the quality standards in equation (2) in the same way as Maximum Tolerable Concentrations (MTCs) are used to evaluate Ecotoxicity. However, the EI values are not necessarily

related to toxic effect, and can only be treated as a screening tool which gives an indication of potentially harmful concentrations released to the environment.

It will be necessary to subdivide the Environmental Irradiation group into terrestrial, aerial and aquatic, and an effect score can be worked out for each. A certain time frame needs to be defined to ensure that cumulative additions of radionuclides from routine discharges do not reach unacceptably high concentrations. In the case of solid waste disposed in a repository, mathematical transport models will be required to predict the final radionuclide concentrations in soil and water. This information may not be readily available, but approximations may be made using data from literature. In the UK, for example, collective doses per unit of disposed radioactive waste have been published for different sites. These values can be used to give an estimate of the concentrations needed in the characterisation stage. We propose that the Environmental Irradiation category be expressed as :

$$C_{ET} = M_i \frac{1}{EI_i} \tag{5}$$

where C_{ET} Potential contribution to Environmental Irradiation from substance j
EI_i Environmental Increment factor for substance j (Bq/kg soil or Bq/m³ water or Bq/m³ air)

The resulting value can be interpreted as the amount of soil, water or air being polluted to the tolerable limit defined as the EI concentration. In this respect, it is closely analogous to the Critical Volumes approach (BUWAL, 1991).

The fate factor has been defined as 1 in equation (5), similarly to Ecotoxicity, but this ignores any consideration of the lifetime of the radionuclides in the environment. This represents a "worst case" assumption and the fate factor needs further definition.

In general, two techniques have evolved which attempt to bring fate into equation (4). These are the "Critical Surface-time" approach (JOLLIET, 1995) and "Multi-media environmental models" (GUINÉE, 1993 & 1996). The advantage of the latter approach is that it includes inter-media transfer of substances when simulating the fate of toxic emissions in the environment. This methodology is not easy to carry out, however, as a wide range of data is required for each substance to be able to perform the calculations. The critical surface-time approach is easier to apply, especially for pollutants with long residence times in the environment. If values of pollutant residence-times and volume of dilution can be directly found in the literature, JOLLIET (1995) proposes that the fate factor can be directly calculated as:

$$F_j = \frac{\tau_j}{V_j} \tag{6}$$

where τ_j Degradation life time of substance j ($t_{1/2}$/ln 2)
V_j Volume of dilution, m³/m² (air, water or soil)

The volume of dilution for water pollution, for example, can be calculated as the world resource in drinking water divided by the earth's surface. This approach is not appropriate, however, for substances with short residence times as these do not have enough time to be diluted in the entire potential volume. In these cases, JOLLIET (1995) proposes to determine the fate factor empirically as the ratio of the measured ambient concentration to the corresponding total emission flow. The dilution volume can then be found using life-times from the literature.

In the case of radionuclides with long half-lives, it may be possible to use the Critical Surface-time approach to bring a fate factor into the proposed Irradiation classification group. Experimental work that helps in determining the dilution volumes is not known, so the volumes used to describe a model world (e.g. volume of air/earth surface area) can be used as a first approximation. If the new fate factor (6) is included in the Environmental Irradiation category, our proposed equation (5) becomes:

$$C_{ET} = M_i x \frac{1}{EI_i} x \frac{\tau_j}{V} \tag{7}$$

where τ_j Degradation life time of radionuclide j
V Volume of dilution, m³/m² (air, water or soil)

3 Example

To illustrate the use of the impact assessment methodology proposed above, the Characterisation factors for Internal Human Radiation and Environmental Irradiation were applied to two different effluent streams from British Nuclear Fuels (BNFL) reprocessing plant. BNFL provides the fuel manufacturing and reprocessing services in the UK. With the newly commissioned Thermal Oxide Reprocessing Plant (THORP) at Sellafield, BNFL has the capability to fabricate and reprocess fuel for all the principal types of commercial reactors. In this example an acidic and an alkaline low active effluent stream discharged to sea from THORP were compared. Both these streams are well within authorised limits. The radionuclides considered were Tc99, Np237, Am241, I129, Pu241 and Sr90. The results in **Table 1** show that the acidic effluent stream has a potentially greater impact on Human Health and the Environment compared to the alkaline stream. This is not surprising as the acidic stream has the higher concentration of radionuclides. More interestingly, however, is that the difference is very much greater for Environmental Irradiation than for Human Radiation. **Figure 1** shows the percentage difference between the impact scores for Human Radiation and Environmental Irradiation for the two streams. Hence, certain radionuclides are considered to have a proportionately greater impact on the environment than on human health. Of the radionuclides considered here, those with the greatest difference between human and environmental effects were found to be Tc99 and Np237. The extent of this effect is shown by the value of the EI/ALI

Table 1: Results

	EI/ALI	Human Radiation C_{ij} (arbitrary measure Bq/Bq) THORP acidic	THORP alkaline	Environmental Irradiation C_{ij} (arbitrary measure yrs m^2) THORP acidic	THORP alkaline
Tc99	6.7E–14	0.81	0.16	1.8E+06	3.5E+05
Np237	1.1E–09	2.15	0.42	3.1E+03	6.0E+02
Am241	1.0E–08	7.93	5.72	2.6E–01	1.9E–01
I129	2.2E–10	8.10	1.43	4.5E+05	8.0E+04
Pu241	2.4E–08	25.10	15.95	9.8E–03	6.2E–03
Sr90	5.0E–06	53.65	46.06	2.1E–04	1.8E–04
	ΣC_{ij}	97.74	69.74	2.2E+06	4.3E+05
	Difference	29 %		80 %	

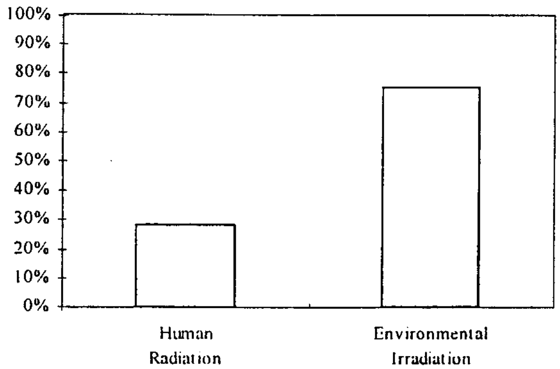

Fig. 1: Percentage difference between acidic stream and alkaline stream for both categories

ratio, given in Table 1. Tc99 and Np237 have very low values for this ratio, showing that the approach proposed here gives much greater weighting to their possible environmental than to their human impacts. Whether this is a real effect or an artefact of anomalously low EI estimates for these two radionuclides remains to be clarified.

This approach implies no relative valuation of human radiation and environmental irradiation. On both grounds, reducing emissions of the acidic stream takes priority over the alkaline stream. However, if the acidic stream can be reduced by 29 % or more, subsequent priorities depend on whether human or ecological effects are considered to be more important. Thus, in the specific case of these two effluent streams from THORP, the methodology proposed here helps to define the decisions which must be made in assessing and improving environmental performance.

4 Conclusions

A new framework has been proposed for the assessment of radionuclides in Life Cycle Assessment. In addition to the potential impacts on human health, there is a need to look at the potential impacts on the environment. A classification group called Environmental Irradiation has therefore been suggested. The proposed methodology is consistent with the other impact assessment procedures in LCA and is based on a weighting factor which expresses the potential contribution by different radionuclides to the category. This factor consists of a measure for environmental protection, the Environmental Increment (EI) values, and a fate factor which is related to the lifetime and volume of dilution of the radionuclides. The Environmental Irradiation category can easily be applied to systems involving the release of radioactive material, and provides an indication of the potential impacts resulting from irradiation of the environment.

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